Ensemble Assimilation of Doppler Radar Observations

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LONG-TERM GOALS

The final goal of this project is to provide the US Navy with an increased capability of using Doppler radar observations in the detection and prediction of hazardous weather events that usually have a strong randomness in nature and affect the Navy operations, especially over oceans and in remote areas. By developing a high-resolution data assimilation capability that can effectively assimilate Doppler radar observations along with other conventional and remotely-sensed data, the US Navy will have the ability to analyze and forecast the battlespace atmospheric conditions with sufficient detail and accuracy for supporting the Navy mission in threat detection, weapons deployment, and weather safe operations.

OBJECTIVES

The objective of the study is to develop an advanced ensemble-based radar data assimilation system for the US Navy and to address some critical scientific and technique issues associated with ensemble radar data assimilation. The radar data system that will be developed will use flow-dependent background error covariance (instead of the static background error covariance) to account for the complexity and rapid change in the dynamical and microphysical structures inside and outside storms. The system will assimilate all the observed variables from different types of sensors, including Doppler radars, satellites, UAVs, and conventional meteorological observations, simultaneously to allow full interactions among the assimilated variables during the data assimilation to keep the balances among the dynamics, thermodynamics and microphysics in the model initial fields. The system will be able to use the observations from many types of radars on different platforms (WSR-88D, DoD meteorological radars and tactical radars both on-land and shipboard, etc.) with an appropriate quality control. Multi-scale data assimilation capability will also be one of the major features of the new radar data assimilation system that allows observational data at different scales to be assimilated concurrently to ensure the scale balance in the ensemble analyses.

APPROACH

The ensemble Kalman filter (EnKF) recently developed at NRL will be the major tool for this study. All the radar data processing and quality control systems previously developed at NRL will be

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extended to cover the ensemble-based data assimilation and integrated into the EnKF for radar data decoding, pre-processing, quality control, bias removal, and observational error estimation. The proposed ensemble radar data assimilation system will assimilate the raw Doppler radial velocity observations directly in the observational space. This will help to reduce the errors induced during the pre-retrieval and interpolation of wind vectors. A data thinning algorithm will also be developed for radar observations to reduce the data density (especially near the radar locations) and hence the data dependency before assimilation. During the last two years, NRL, NSSL and OU have jointly developed a data thinning algorithm for Doppler radial velocity. This algorithm will be further refined and used in the proposed ensemble radar data assimilation system. The NRL 3D Radar Mosaic will serve as the reflectivity data thinning algorithm.

The forward radar observation operators previously developed at NRL for the 3d/3.5d-Var will be adapted for estimating the radar observations in observational space from ensemble forecasts. For storm-scale data assimilation, one of the biggest challenges is the missing storms in the background fields so that there are no estimated radar observations available at observation locations for the data assimilation. The use of ensemble forecasts as the background should have some advantages over the use of a single deterministic forecast in this aspect. But appropriate ensemble spread that covers all the uncertainties of the model forecasts is critical. An adaptive inflation algorithm previously developed for the EnKF will be refined for radar data to assure the appropriate ensemble spread in both the ensemble analyses and forecasts.

Localization is a necessary step in all ensemble-based data assimilation systems to account for the insufficient ensemble size due to the lack of computational power. The length scale of the localization is a very sensitive parameter that affects the ensemble analyses. The assimilation of storm-scale data along with the large- and synoptic-scale observations makes this challenging issue even much more complicated. In this study, we will develop an observation-adaptive, variable-dependent, multi-scale localization algorithm. This algorithm will use a multiple-localization procedure and determine the localization scale based on observational data type, the control variable, and the statistics of the observational and background errors.

Experiments of ensemble radar data assimilation with simulated and real observations will be conducted and the results will be compared with those from the 3d/3.5d-Var. This will help to investigate the impact of the flow-dependent background error covariance on analyses and forecasts. Furthermore, the comparisons between the variational and ensemble-based approaches will also be very useful in the development of a future hybrid radar data assimilation system.

WORK COMPLETED

During the fiscal year 2010, research and development efforts were focused on enhancing NRL capability in acquisition, processing, quality control, and assimilation of Doppler radar observations from DoD shipboard radars and other radar networks into the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) for nowcasting and forecasting high-impact weather events that affect Navy operations over oceans. A lossless differential compression algorithm was developed to further reduce the data size of weather radar observations in Universal Format (UF). Algorithms for super-obs of Doppler radial velocity were adapted, tested and integrated into NRL radar data assimilation system to thin the radar observations before data assimilation. Software was

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also developed to integrate radar observations into NRL Atmospheric Variational Data Assimilation System (**NAVDAS**) innovation vectors so that the radar data are available not only to the NRL EnKF but also to all other NRL data assimilation systems for assimilation. In addition, research efforts were also made to further improve the NRL EnKF to make the system ready for assimilating Doppler radar observations and to increase the system's ability in estimating flow-dependent background error covariance at storm-scale as well. Following are the details of the work tasks completed during FY10:

1) The NRL capability in acquisition, processing and quality control of the real-time Doppler radar observations of reflectivity and radial velocity from both WSR-88D networks and SPS-48E shipboard radars was further advanced to a new level. A lossless differential compression of weather radar data in Universal Format (UF) using motion estimation and compensation was developed by Dr. David Pan (University of Alabama) by working with NRL scientists. The algorithm was delivered to NRL and integrated into the UF Data Compressor (UFZIP), an innovative technique developed at NRL (also by Dr. Pan) in 2008 that compresses the raw (level-II) SPS-48E/G Doppler radar data and allows the transfer of near real-time radar observations from ships to Fleet Numerical Meteorology and Oceanography Center (FNMOC) for assimilation into COAMPS with limited bandwidth. This new technique outperforms the previous UFZIP in data size reduction by removing temporal redundancies in weather radar data. In addition, two new algorithms for ground and sea clutter detection and removal are also under development and test.

2) Algorithms were adapted from the National Severe Storms Laboratory (NSSL) for super-observations of Doppler radial velocity after data quality control. These algorithms were originally developed by Dr. Qin Xu and his students at the University of Oklahoma (Xu et al., 2006) with the support from ONR. These algorithms were recently transitioned to NRL, modified and integrated into NRL radar data assimilation system to improve effectiveness and efficiency of Doppler radial velocity assimilation into COAMPS by reducing information redundancy and spatial correlation of radar observations, especially near the radar station.

3) Algorithms and software were developed to integrate Doppler radar observations, after quality control and super-obs, into NRL NAVDAS innovation vector files. By adding forward operators for both Doppler radial velocity and reflectivity to NAVDAS, the background fields of Doppler radial velocity and reflectivity are also computed from COAMPS forecasts of three-dimensional winds (u, v, w) and microphysical fields. This work provides the observational radar data to the EnKF for assimilation into COAMPS. Meanwhile, it also makes the radar data available to other NRL data assimilation systems (the 3D-Var and the 4D-Var) and paves the way to assimilate the radar observations into any of these variational data assimilation systems. These algorithms and software are currently under test.

4) Another significant accomplishment of this project in the past physical year was the further improvement of the NRL EnKF for ensemble assimilation of radar observations into COAMPS. The COAMPS nested-grid capability was built into the EnKF that adds the capability of providing storm-scale background error covariance from COAMPS ensemble forecasts. The localization algorithm was also enhanced for optimal assimilation of storm-scale data along with large-scale conventional observations. Several inflation algorithms were tested to ensure the appropriate ensemble spreads that cover all the uncertainties in both model forecasts and observations. Observations of satellite winds and temperature profiles were added to the EnKF that increases the number of observations over oceans where radar observations are usually

RESULTS

1. The lossless differential compression of weather radar data in Universal Format

A series of radar scans taken approximately 5 minutes apart contain storm motions. Apparently, there are some similarities in storm patterns between any two temporally adjacent scans. By applying the motion estimation and motion compensation (ME/MC) technique developed by Pan et al (2010), the temporal redundancies in storm information among a series of radar scans can be removed and data size can be reduced without losing any storm information. Figure 1 gives the results of the radar data size after compression by the ME/MC method (the Inter curve in Fig. 1) from an experiment with 250 SPS-48E level-II (raw) volumetric scans that contains reflectivity, radial velocity, and spectrum width observations. Figure 1 also compares the results with those from the radar data compression technique previously developed at NRL based on bzip2 method (the Intra curve in Fig. 1). It is obvious that the ME/MC algorithm outperforms the bzip2 method in data size reduction. More importantly, ME/MC technique is lossless in data information while the bzip2 is a lossy method that usually results in some information loss.

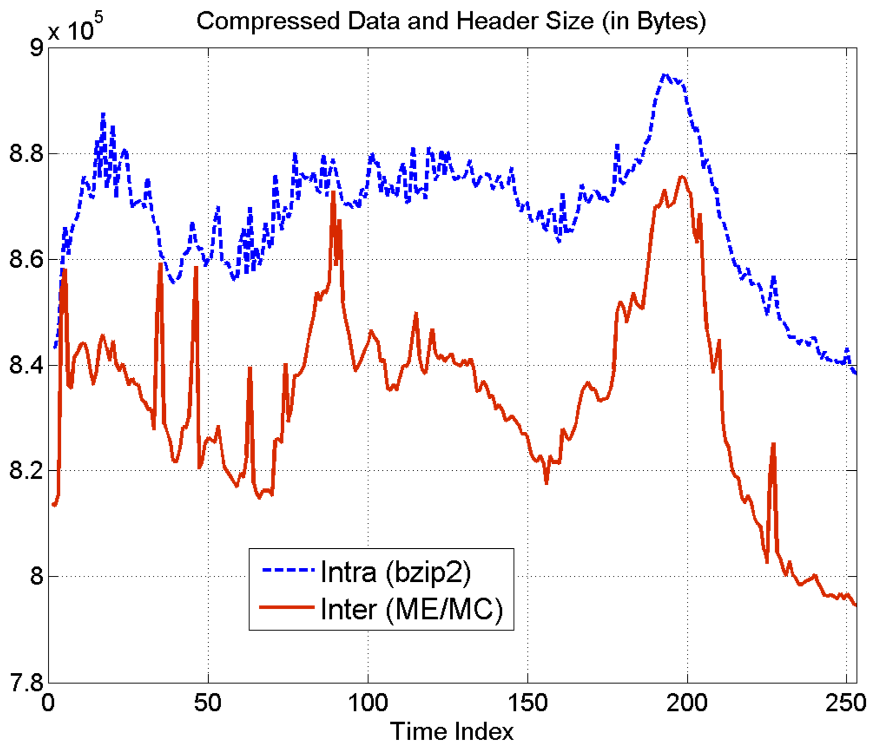

Fig. 1. Comparison of the sizes of the compressed radar level-II (raw) scan data (reflectivity, radial velocity, and Spectrum width) and headers between the inter-file compression method based on ME/MC, and the intra-file compression method based on bzip2.

2. Super-observations of Doppler radial velocity

Theoretical analyses suggest that there can be a significant degree of information redundancy in radar observations if the observations are too dense to be resolved by an optimal analysis with a given background error covariance. Even for storm-scale radar data assimilation with an EnKF that estimates the background error covariance from an ensemble of model predicted fields on a high-resolution model grid with much finer structures, the conventional (level-II) radar data may still have excessive accuracy and resolution, especially at locations close to the radar station, if the covariance is estimated from a small ensemble of imperfect-model predictions and thus contains significant errors and spurious noisy structures. To achieve high computational efficiency and to reduce the spatial information redundancy, a system for super-observations of Doppler radial velocity was developed by Dr. Qin Xu at NSSL and his research group at the University of Oklahoma. In this system, super-obs of Doppler radial velocity can be computed over two types of grid: a grid box or a sector block (both on conical radar scan surfaces). Since NRL NAVDAS assimilates observations in observational space, the sector blocks were selected as the super-obs grid system. Figure 2 shows an example of a radar PPI scan of Doppler radial velocity before and after super-obs.

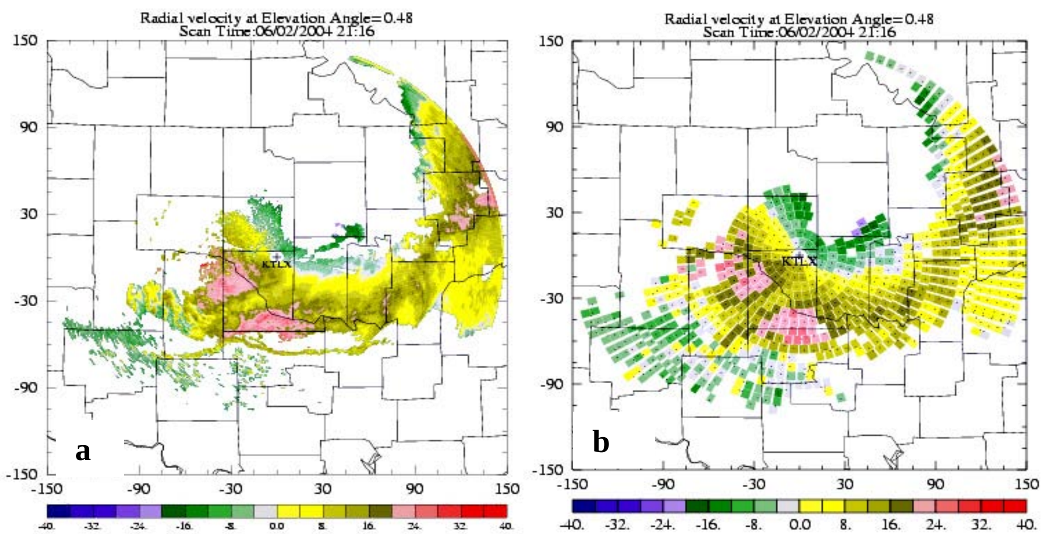

Fig. 2. (a) Doppler radial-velocity (ms^{-1}) observed by the WSR-88D radar in Norman, Oklahoma at 21:16 UTC 2 June 2004 with an elevation angle of 0.48 degree, and (b) the super-observations computed over sector blocks from (a).

Several algorithms for computing the value of super-obs inside a sector block were tested. These algorithms include least square fitting (LSF), correlation function (CF), simple averaging (SA), Cressman method (CM), and singular vector decomposition (SV). Table 1 gives the root-mean-square (RMS) errors of the computed super-obs from these algorithms and the computer CPU time needed. These numbers were from an experiment with a simulated Doppler radial velocity field (Xu et al. 2006). Based on this study, the SA method overall had the second smallest RMS errors and the lowest computational cost, and hence was selected as the super-obs computation algorithm for the ensemble radar data assimilation at NRL.

3. Improvements in NRL EnKF for radar data assimilation

As mentioned in previous section, the NRL EnKF has been improved significantly during the past year with several newly-added capabilities for handling storm-scale data assimilation. Extensive tests have been conducted to test the EnKF with different types of storms and different types of observations to ensure that the system can effectively assimilate most types of observations ranging from large-scale to storm-scales. Now, the system is ready for Doppler radar data assimilation.

Table 2. RMS errors of the computed radial velocity super-obs with different computing algorithms and the computer CPU times needed (by setting the CPU time for the SA method to 1.0).

RMS error (ms^{-1})		Range 0~ 80 km					Range 80 km ~ 150 km				
Methods		LSF	CF	SA	CM	SV	LSF	CF	SA	SV	CM
Grid size	3 km	0.291	0.291	0.291	0.296	0.291	0.371	0.371	0.371	0.371	0.375
	6 km	0.162	0.163	0.163	0.164	0.166	0.207	0.207	0.207	0.208	0.212
	9 km	0.123	0.125	0.125	0.126	0.133	0.149	0.150	0.150	0.152	0.152
	12 km	0.103	0.108	0.108	0.109	0.120	0.115	0.117	0.117	0.120	0.118
	18 km	0.111	0.129	0.129	0.127	0.141	0.121	0.129	0.129	0.131	0.123
CPU time ratio		2.22	2.33	1	1.22	10.67					

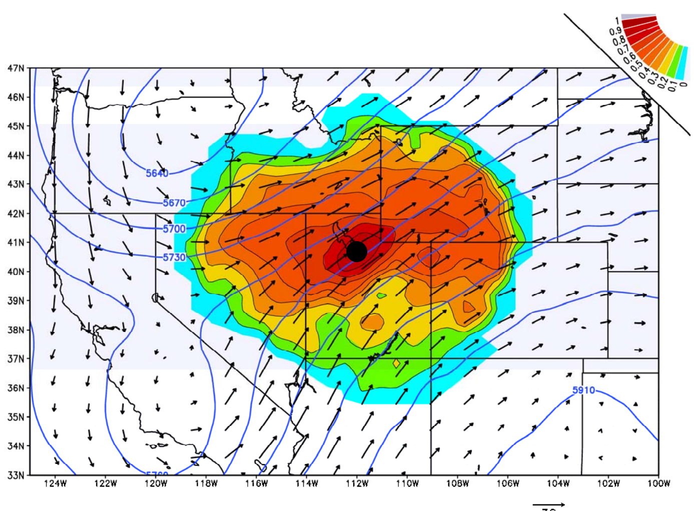

Fig. 3. Horizontal background error correlation (colored with a level interval of 0.1) for a temperature observation at 500 hPa (the dot) estimated by the EnKF from COAMPS ensemble forecasts of 32 members. The blue contours and the black vectors are the geopotential height (in meter) and horizontal winds (ms^{-1}) on 500 hPa pressure surface, respectively.

An example of horizontal background error correlation estimated by the EnKF from 32 members of COAMPS ensemble forecasts is presented in figure 3. The background error correlation was for a temperature observation at 500 hPa located inside a storm associated with a deep trough along the West Coast of US. It is obvious that this ensemble-based background error correlation is spatially inhomogeneous and basically reflects the dynamic structures of the storm system. This ensemble background error correlation looks more dynamically related and realistic than the pre-defined, static, homogeneous background error correlation used by the current operational NAVDAS 3D-Var for COAMPS and is especially important for storm-scale radar data assimilation which usually has strong nonlinearity and spatial inhomogeneity.

Observational data impact study was also conducted with the EnKF for wind data assimilation. Let d_i^b denote the innovation vector at the ith observation (y_i), then we have

$$d_i^b = [y_i - H_i(X_b)] \qquad (1)$$

where H is the forward operator and X_b the background from the mean of the previous ensemble forecasts without data assimilation. Similarly, the innovation vector at the same observation after the data assimilation, d_i^a, becomes

$$d_i^a = [y_i - H_i(X_a)] \qquad (2)$$

where X_a is the background from the ensemble mean of the EnKF analyses after data assimilation. Then the difference

$$D_i = abs(d_i^b) - abs(d_i^a) \qquad (3)$$

indicates the reduction of the innovation at the ith observation due to the assimilation of all the observations before the ith observation. Figures 4a and 4b give the values of D at all observation locations for the assimilation of u and v, respectively. Apparently, the EnKF assimilates the wind observations very effectively. This is an important indication that the EnKF is suitable for the assimilation of Doppler radial velocity observations.

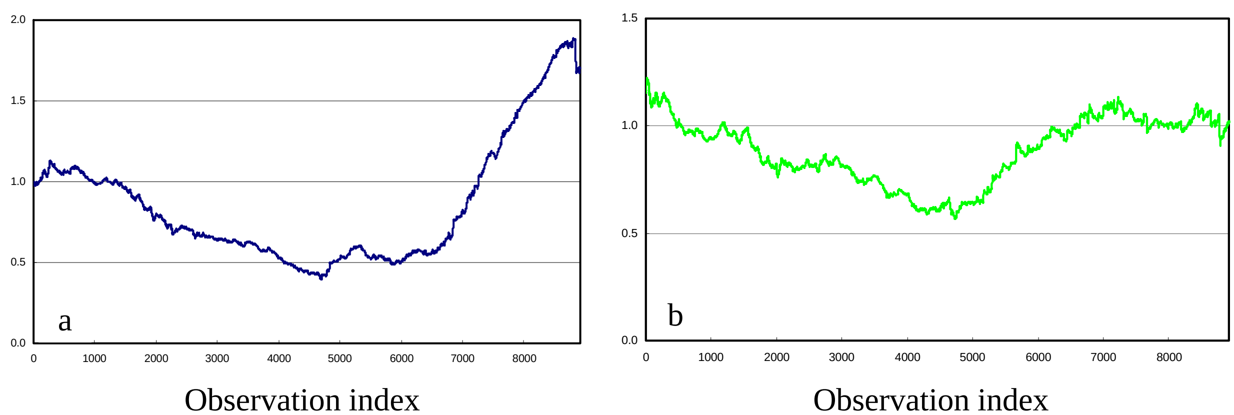

Fig. 4. Reduction of innovations (ms^{-1}) at all observation locations (a) due to the assimilation of u and (b) due to the assimilation of v.

The landfall of Hurricane Gustav on Louisiana in 2008 was also selected to test the EnKF. Figure 5a gives the ensemble mean of sea level pressure from the 24-hour COAMPS ensemble forecasts with 32 members initialized by the EnKF. For comparison, the same field from the COAMPS 24-hour forecast initialized with the operational NAVDAS 3D-Var is also given in Fig. 5b. Figure 5c is the surface analysis map valid at the same time for validation. While there is no notable difference between the locations of the hurricane center in Figs 5a and 5b, the minimum sea level pressure at the hurricane center in Fig. 5a is lower than that in Fig. 5b and closer to the observed value of 1000 hPa shown in Fig. 5c. Although this is just one case study, it shows that the EnKF is now a system capable of producing analyses and forecasts comparable to the operational NAVDAS 3D-Var for COAMPS.

Figures 6a, 6b and 6c show the ensemble spreads of temperature and horizontal wind speed of the ensemble analyses, the 24-hour and 48-hour ensemble forecasts, respectively, at 500 hPa for the same case. Notable ensemble spreads of both temperature and wind fields are founded mainly within the storm regions (see Fig. 5) where considerable amount of uncertainties in the analyses and forecasts exist. This is a proof that the EnKF has the ability to account for the uncertainties in observations and model forecasts, an important feature for storm-scale radar data assimilation.

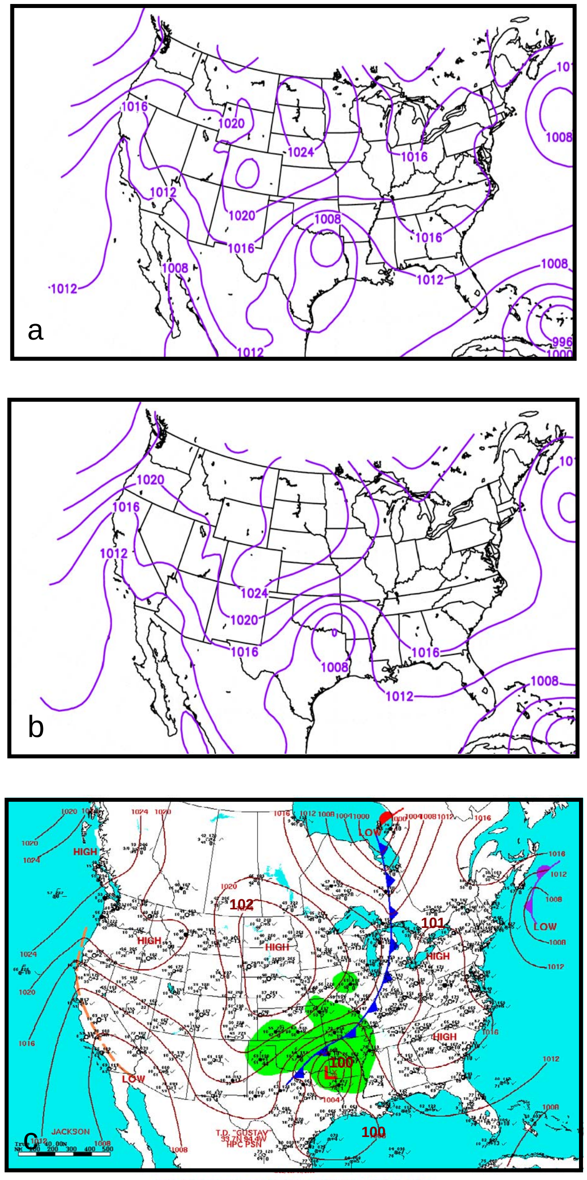

Fig. 5. (a) 24-hour forecast (valid at 1200 UTC 3 September 2008) of sea level pressure (hPa) of Hurricane Gustav after landfall on Louisiana from the mean of COAMPS ensemble forecasts of 32 members initialized by the EnKF, (b) same as (a) except from the COAMPS forecast initialized by the NAVDAS 3D-Var, and (c) the surface map.

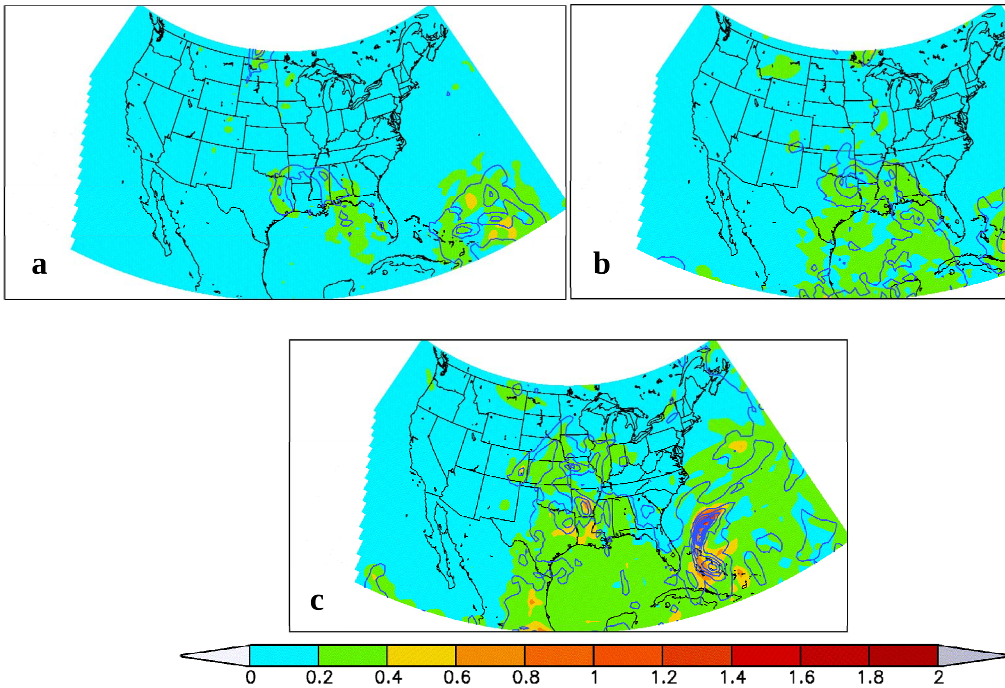

Fig. 6. Ensemble spreads of temperature (colored, degree) and wind speed (contours with an interval of 1 ms^{-1}) at 500 hPa from (a) the 32 EnKF analyses, (b) 24-hour COAMPS ensemble forecasts, and (c) 48-hour COAMPS ensemble forecasts.

IMPACT/APPLICATIONS

Real-time applications and several transitions have been made from the efforts of developing NRL radar data processing, quality control and assimilation capabilities. The NRL Doppler Radar Data Processing and Quality Control System and the NRL 3D Radar Mosaic are now mature systems for processing real-time radar observations from both S-band and C-band Doppler radars, including the DoD meteorological and tactical radars (such as the land-based Supplemental Weather Radars, or SWR, and shipboard SPS-48E and SPY-1) and those in the WSR-88D Network, with various data formats. These systems also supported the NRL Nowcasting Demo at the Naval Strike and Air Warfare Center (NSAWC) at Fallon, Nevada for providing real-time analyses and nowcasting of weather conditions for Navy pilot training. The Lossless Differential Compression of Weather Doppler Radar Technique significantly compresses the shipboard SPS-48E and SPY-1 Doppler radar UF format data files to ensure the real-time transfer of the full-volume, full-resolution radar observations from ships with limited bandwidth to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for data assimilation. In addition, the 3d/3.5d-Var radar data assimilation systems are planned to transition to FNMOC.

TRANSITIONS

The weather radar data compression software developed in FY-09/10 has been transitioned to the Hazardous Weather Detection and Display Capability (HWDDC) through a SPAWAR 6.4 project. The HWDDC is be integrated with the SPS-48E radar systems onboard twelve U.S. Navy aircraft carriers and amphibious assault ships. The first ship installation of the HWDDC will be in the 1st quarter of FY-11.

RELATED PROJECTS

Related NRL base projects include the 6.2 task BE-435-047, Advanced Assimilation of Non-conventional Data for Improved High-Impact Weather Prediction. Other related projects include Radar Data Quality Control and Assimilation At the National Weather Radar Testbed (NWRT), 6.4 Reach-Back Doppler Radar Data Assimilation (PMW-120, X2341) and 6.4 On-Scene Tactical Atmospheric Forecast Capability (PMW-120, X2342).

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